

Charm fragmentation and excited charm and charm-strange mesons at ZEUS

Leonid Gladilin* (on behalf of the ZEUS collaboration)

Moscow State University - Scobeltsyn Institute of Nuclear Physics
1(2), Leninskie gory, GSP-1, Moscow 119991 - Russia
E-mail: gladilin@sinp.msu.ru

The charm fragmentation function has been measured in photoproduction of jets containing $D^{*\pm}$ mesons. The measured function has been used to extract free parameters of different fragmentation models. Measurements of excited charm, $D_1(2420)^0$ and $D_2^*(2460)^0$, and charm-strange, $D_{s1}(2536)^\pm$, mesons and a search for the radially excited charm meson, $D^{*'}(2640)^\pm$, were also performed. The results are compared with those measured previously and with theoretical expectations [1].

1 Introduction

Charm hadrons were produced copiously in ep collisions with a centre-of-mass energy of 318 GeV at HERA providing a means to study charm hadronisation. During first phase of the HERA operation (1992-2000), the ZEUS collaboration accumulated data sample corresponding to an integrated luminosity of $\sim 120 \text{ pb}^{-1}$. Measurements of the D^{*+} , D^0 , D^+ and Λ_c^+ production^a with the HERA I data were used to determine charm fragmentation ratios and fractions of c quarks hadronising as a particular charm hadron, $f(c \rightarrow D, \Lambda_c)$, in earlier ZEUS studies [2, 3]. Recent ZEUS measurements of the charm fragmentation function [4] and the production of excited charm and charm-strange mesons [5] are summarised in this note.

2 Measurement of charm fragmentation function

The measurement of the charm fragmentation function in the transition from a charm quark to a D^{*+} meson was performed in photoproduction regime with the virtuality of the exchanged photon $Q^2 < 1 \text{ GeV}^2$ and the photon-proton centre-of-mass energy in the range $130 < W < 280 \text{ GeV}$. The D^{*+} mesons were reconstructed from the decay chain $D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+$ using the mass difference technique. The D^{*+} meson was included in the jet-finding procedure and was thereby uniquely associated with one jet only. The fragmentation variable, z , was defined as

$$z = (E + p_{||})^{D^{*+}} / (E + p_{||})^{\text{jet}} \equiv (E + p_{||})^{D^{*+}} / 2 E^{\text{jet}},$$

where $p_{||}$ is the longitudinal momentum of the D^{*+} meson or of the jet relative to the axis of the jet of energy E^{jet} . The equivalence of $(E + p_{||})^{\text{jet}}$ and $2 E^{\text{jet}}$ arises because the jets were reconstructed as massless objects. The measurement of the normalised differential cross section, $1/\sigma(d\sigma/dz)$, was performed in the kinematic range $p_T(D^{*+}) > 2 \text{ GeV}$, $|\eta(D^{*+})| < 1.5$, $E_T^{\text{jet}} > 9 \text{ GeV}$ and $|\eta^{\text{jet}}| < 2.4$. The above requirements on $p_T(D^{*+})$ and E_T^{jet} allowed the fragmentation function measurement in the range $0.16 < z < 1$.

*Participation in DIS 2009 was supported by the Deutsches Elektronen-Synchrotron DESY

^aHereafter, charge conjugation is implied.

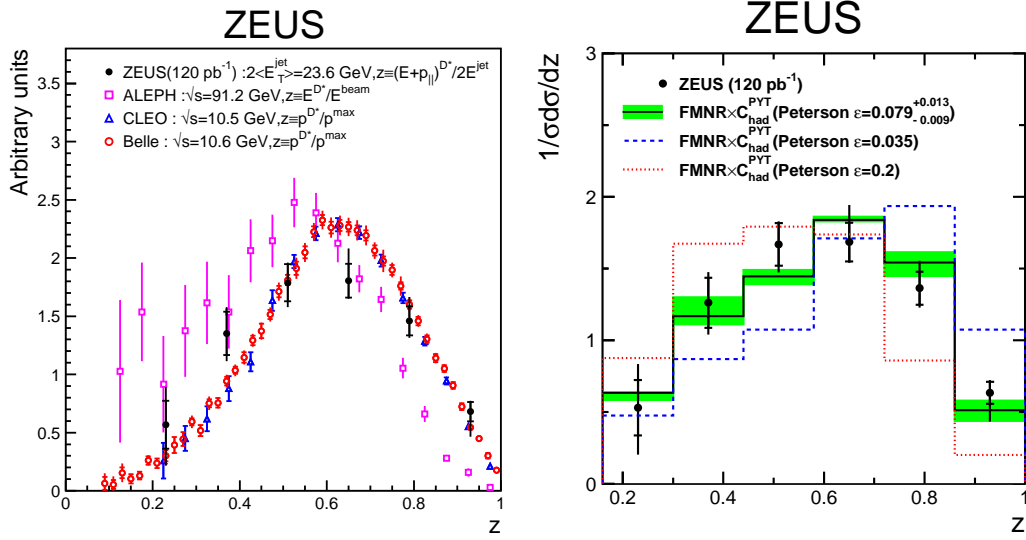


Figure 1: Charm fragmentation function in transition to D^{*+} for the ZEUS data compared to (left) measurements in e^+e^- annihilations and (right) predictions of $\text{FMNR} \times C_{\text{had}}^{\text{PYT}}$.

The measured fragmentation function is compared in Fig. 1(left) with previous measurements from Belle [6], CLEO [7] and ALEPH [8]. For shape comparison, the data sets were normalised to $1/(\text{bin width})$ for $z > 0.3$. The Belle and CLEO data are measured at a centre-of-mass energy of ~ 10.5 GeV, whereas the ALEPH data were taken at 91.2 GeV. The corresponding scale of the ZEUS data is given by twice the average transverse energy of the jet, 23.6 GeV. The ZEUS data in Fig. 1(left) are shifted somewhat to lower values of z compared to the CLEO and BELLE data with the ALEPH data even lower that is consistent with expectations from scaling violations in QCD.

The ZEUS data were compared with fragmentation models implemented in the leading-logarithmic Monte Carlo (MC) program PYTHIA [9]. The LUND string fragmentation model [10] modified for heavy quarks [11] gives a reasonable description of the data. The PYTHIA predictions obtained using the Peterson fragmentation function [12] was fit to the data via a χ^2 -minimisation procedure to determine the best value of the parameter ϵ . The result of the fit is $\epsilon = 0.062 \pm 0.007^{+0.008}_{-0.004}$. The result is in reasonable agreement with the default value used in PYTHIA (0.05), with the value measured by the H1 collaboration in deep inelastic scattering ($0.061^{+0.011}_{-0.009}$) [13], and with the value 0.053 obtained in the leading-logarithmic fit [14] to the ARGUS data [15].

The data were also compared with the next-to-leading-order (NLO) QCD predictions from Frixione et al. (FMNR) [16]. The predictions with the parton-level jets were translated to the predictions with the hadron-level jets using the hadronisation correction factors, $C_{\text{had}}^{\text{PYT}}$, obtained with the PYTHIA MC. The result of varying ϵ in the Peterson function for the predictions of $\text{FMNR} \times C_{\text{had}}^{\text{PYT}}$ is shown in the Fig. 1(right). The fit result, $\epsilon = 0.079 \pm 0.008^{+0.010}_{-0.005}$, exceeds the value 0.035 obtained from the NLO fit [14] to the ARGUS data [15]. The fit of the $\text{FMNR} \times C_{\text{had}}^{\text{PYT}}$ predictions with the fragmentation function from Kartvelishvili et al. [17] yielded the value of the free parameter $\alpha = 2.67 \pm 0.18^{+0.17}_{-0.25}$.

3 Production of excited charm and charm-strange mesons

The first study of excited charm and charm-strange mesons produced in ep collisions was restricted to decays, for which significant signals were identified:

$$\begin{aligned} D_1(2420)^0 &\rightarrow D^{*+}\pi^-, \\ D_2^*(2460)^0 &\rightarrow D^{*+}\pi^-, D^+\pi^-, \\ D_{s1}(2536)^+ &\rightarrow D^{*+}K_S^0, D^{*0}K^+. \end{aligned}$$

The measurement was performed in the full kinematic range of Q^2 . The D^{*+} mesons were identified using the decay channel $D^{*+} \rightarrow D^0\pi^+$ following by either $D^0 \rightarrow K^-\pi^+$ or $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decay. The D^+ mesons were reconstructed in the decay $D^+ \rightarrow K^-\pi^+\pi^+$. The D^{*0} mesons were tagged in the decay to a D^0 and undetected neutrals following by the $D^0 \rightarrow K^-\pi^+$ decay.

To extract the D_1^0 and D_2^{*0} yields and properties, a minimal χ^2 fit was performed using simultaneously the $M(D^+\pi^-)$ distribution and the $M(D^{*+}\pi^-)$ distributions in four helicity intervals. The helicity angle (α) is defined as the angle between the momenta of the additional pion and the pion from the D^{*+} decay in the D^{*+} rest frame. The helicity angular distribution can be parametrised as

$$\frac{dN}{d\cos\alpha} \propto 1 + h \cos^2\alpha, \quad (1)$$

where h is the helicity parameter. Heavy Quark Effective Theory [18] (HQET) predicts $h = 3$ ($h = 0$) for the 1^+ state from the $j = 3/2$ ($j = 1/2$) doublet, and $h = -1$ for the 2^+ state from the $j = 3/2$ doublet. Only D -wave decays are allowed for the members of the $j = 3/2$ doublet; therefore they are supposed to be narrow. On the other hand, the members of the $j = 1/2$ doublet decay through S -wave only and therefore are expected to be broader [19]. Due to the finite charm quark mass a separation of the two doublets is only an approximation and amplitudes of two observable states with $J^P = 1^+$ can be mixtures of D - and S -wave amplitudes.

The measured masses of the D_1^0 and D_2^{*0} are in reasonable agreement with the world average values [20]. The measured D_1^0 width is $\Gamma(D_1^0) = 53.2 \pm 7.2_{-4.9}^{+3.3}$ MeV which is above the world average value 20.4 ± 1.7 MeV [20]. The observed difference can be a consequence of differing production environments. The D_1^0 width can have a sizeable contribution from the broad S -wave decay even if the S -wave admixture is small [21]. A larger S -wave admixture at ZEUS with respect to that in measurements with restricted phase space, which can suppress production of the broad state, could explain why the measured D_1^0 width is larger than the world average value.

The measured D_1^0 helicity parameter is $h(D_1^0) = 5.9_{-1.7}^{+3.0+2.4}_{-1.0}$ which is inconsistent with the prediction for a pure S -wave decay of the 1^+ state, $h = 0$. It is consistent with the prediction for a pure D -wave decay, $h = 3$. In the general case of D - and S -wave mixing, the helicity angular distribution form of the 1^+ state is:

$$\frac{dN}{d\cos\alpha} \propto r + (1-r)(1 + 3\cos^2\alpha)/2 + \sqrt{2r(1-r)}\cos\phi(1 - 3\cos^2\alpha), \quad (2)$$

where $r = \Gamma_S/(\Gamma_S + \Gamma_D)$, $\Gamma_{S/D}$ is the S -/ D -wave partial width and ϕ is the relative phase between the two amplitudes. Using Eqs. (1) and (2), $\cos\phi$ can be expressed in terms of r

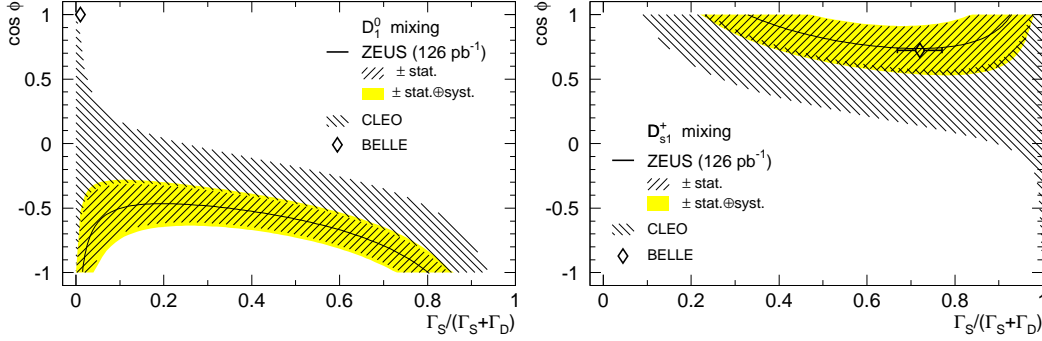


Figure 2: Cosine of the relative phase of S - and D -wave amplitudes versus $r = \Gamma_S / (\Gamma_S + \Gamma_D)$ in (left) the $D_1(2420)^0 \rightarrow D^{*+}\pi^-$ decay and (right) the $D_{s1}(2536)^+ \rightarrow D^{*+}K_S^0$ decay.

and the measured value of the helicity parameter, h :

$$\cos \phi = \frac{(3 - h)/(3 + h) - r}{2\sqrt{2r(1 - r)}}. \quad (3)$$

Figure 2(left) compares with previous measurements the range restricted by the measured $h(D_1^0)$ value and its uncertainties in a plot of $\cos \phi$ versus r . The ZEUS range has a marginal overlap with that restricted by the CLEO measurement of $h(D_1^0) = 2.74_{-0.93}^{+1.40}$ [22]. BELLE performed a three-angle analysis and measured both the $\cos \phi$ and r values [23]. The BELLE measurement, which suggested a very small admixture of S -wave to the $D_1(2420)^0 \rightarrow D^{*+}\pi^-$ decay and almost zero phase between two amplitudes, is outside the ZEUS range; the difference between the two measurements, evaluated with Eq. (3), is ~ 2 standard deviations.

A signal from the $D_{s1}^+ \rightarrow D^{*0}K^+$ decay was observed in the $M(D^0K^+)$ distribution with an average negative shift of 142.4 ± 0.2 MeV with respect to the nominal D_{s1}^+ mass. To extract the D_{s1}^+ yields and properties, an unbinned likelihood fit was performed using simultaneously values of $M(D^0K^+)$, $M(D^{*+}K_S^0)$, and $\cos(\alpha)$ for $D^{*+}K_S^0$ combinations, with the helicity angle defined as the angle between the momenta of K_S^0 and the pion from the D^{*+} decay in the D^{*+} rest frame.

The measured D_{s1}^+ mass is in good agreement with the world average values [20]. The measured D_{s1}^+ helicity parameter is $h(D_{s1}^+) = -0.74_{-0.17-0.05}^{+0.23+0.06}$. The measured h value is inconsistent with the prediction for a pure D -wave decay of the 1^+ state, $h = 3$, and is barely consistent with the prediction for a pure S -wave decay, $h = 0$. Figure 2(right) shows a range, restricted by the measured $h(D_{s1}^+)$ value and its uncertainties, in a plot of $\cos \phi$ versus $r = \Gamma_S / (\Gamma_S + \Gamma_D)$ (Eq. 3). The measurement suggests a significant contribution of both D - and S -wave amplitudes to the $D_{s1}(2536)^+ \rightarrow D^{*+}K_S^0$ decay. The ZEUS range agrees with that restricted by the CLEO measurement of $h(D_{s1}^+) = -0.23_{-0.32}^{+0.40}$ [24] and with the BELLE three-angle measurement of both $\cos \phi$ and r values [25].

The measured yields were converted to the fragmentation fractions $f(c \rightarrow D_1^0) = 3.5 \pm 0.4_{-0.6}^{+0.4} \%$, $f(c \rightarrow D_2^{*0}) = 3.8 \pm 0.7_{-0.6}^{+0.5} \%$ and $f(c \rightarrow D_{s1}^+) = 1.11 \pm 0.16_{-0.10}^{+0.08} \%$. The fractions are consistent with those obtained in e^+e^- annihilations. The measured ratios of

the dominant D_2^{*0} and D_{s1}^+ branching fractions are

$$\frac{\mathcal{B}_{D_2^{*0} \rightarrow D^+ \pi^-}}{\mathcal{B}_{D_2^{*0} \rightarrow D^{*+} \pi^-}} = 2.8 \pm 0.8^{+0.5}_{-0.6} \quad , \quad \frac{\mathcal{B}_{D_{s1}^+ \rightarrow D^{*0} K^+}}{\mathcal{B}_{D_{s1}^+ \rightarrow D^{*+} K^0}} = 2.3 \pm 0.6 \pm 0.3$$

in agreement with the world average values [20].

No radially excited $D^{*'+}$ meson, reported by DELPHI [26], was observed. An upper limit, stronger than that obtained by OPAL [27], was set on the product of the fraction of c quarks hadronising as a $D^{*'+}$ meson and the branching fraction of the $D^{*'+} \rightarrow D^{*+} \pi^+ \pi^-$ decay in the range of the $D^{*'+}$ mass from 2.59 to 2.69 GeV:

$$f(c \rightarrow D^{*'+}) \cdot \mathcal{B}_{D^{*'+} \rightarrow D^{*+} \pi^+ \pi^-} < 0.4\% \quad (95\% \text{ C.L.}).$$

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